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ADVANCES IN THE STUDY OF SOLIDS DEPOSITION IN GEOTHERMAL SYSTEMS

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Abstract - The International Workshop on Deposition of Solids in Geothermal Systems was held in August 1988. Papers were presented on field and laboratory studies of scale deposition from geothermal fluids and in geothermal reservoirs. Scale types investigated included carbonate minerals, amorphous silicates, and mixed metal oxides and sulfides. Scale formation was reported to occur in geothermal systems under a wide range of enthalpy and chemical conditions. The predominant factors found to control the solubility of scale-forming minerals include changes in temperature and pH with lesser control being exerted by the concentrations of other ionic species and by kinetic effects. The range of conditions under which scale mineral formation occurs has resulted in the deposition of these minerals throughout the geothermal utilization system including production wells, surface equipment, and wastewater reinjection wells. Chemical and engineering methods applied to the treatment of scale-forming minerals during extraction of geothermal heat included the addition of chemical inhibitors, control of fluid pressures and temperatures, and mechanical and chemical removal of deposited scale minerals. The work reported at the conference indicated that the success of these methods was somewhat limited, and additional work was recommended on more effective methods of chemical inhibition of scale mineral deposition.

INTRODUCTION

In August, 1988, the International Workshop on Deposition of Solids in Geothermal Systems was held in Reykjavik, Iceland. Its objective was to bring together scientists and engineers conducting research on the physical and chemical processes associated with scale deposition from geothermal fluids and to discuss what is currently known about the deposition process. At the conclusion of the workshop, working groups were formed to discuss future research directions that might best address current practical problems in the production of geothermal fluids for power generation and direct heat applications. This paper presents a review of the workshop papers; a following paper (Thomas and Gudmundsson, 1989) will summarize the results of the working groups' recommendations.

Worldwide production of geothermal fluids accounts for more than 4800 MW of electrical production, and many times that amount of thermal energy is produced for direct heat applications. For all but the simplest applications, the utilization of geothermal heat requires one or more drillholes for the withdrawal of high temperature fluids from the ground, surface utilization equipment (e.g. steam turbines or heat exchangers, and associated fluid handling equipment), and a fluid disposal system (percolation ponds or

reinjection wells). At each stage of the geothermal utilization process, the natural hydrothermal fluids that may have been at thermal and chemical equilibrium with heated reservoir rocks can be exposed to substantial changes in temperature or pressure, which can affect the solubility of a variety of dissolved mineral species. Lowering of the fluid temperatures can decrease the solubility of dissolved silica or metal sulfide species and allow them to precipitate individually or together. Changes in fluid pressure can allow a change of state to take place: either boiling of the liquid or exsolution of dissolved gases. Boiling decreases both the volume of the residual fluids and their temperature, thereby simultaneously increasing the concentration of the dissolved solids present and decreasing their solubility. Loss of dissolved gases (e.g. CO_2 and H_2S) from the fluid (with or without boiling) can also drastically affect the pH, and therefore the solubility, of both sulfide and carbonate minerals. Because the chemical and physical phenomena that affect the individual scale-forming minerals can occur at a variety of locations in a geothermal facility, each of the scale types will be considered individually as it occurs throughout the geothermal process chemistry.

CARBONATE SCALE

Calcium carbonate deposition from medium and high enthalpy fluids is a major problem in a variety of geothermal areas. The most common polymorphs of calcium carbonate include vaterite, calcite, and aragonite. Vaterite is reported to be the first mineral to form from a supersaturated calcium carbonate solution under laboratory conditions (Dalas and Koutsoukos, 1989); it is apparently unstable, however, recrystallizing to form the more stable calcite. This process is in agreement with the results of Arnorsson (1989), who reports that the most frequently observed calcium carbonate scale minerals are calcite and aragonite with the former predominating. Key controls over carbonate scale deposition are the calcium concentrations and total salinity of the reservoir fluids, and the location of first flashing of the geothermal fluid as it is removed from the reservoir. Arnorsson (1989) points out that, because temperature-sensitive mineral buffers appear to control the former parameter, maximum calcium concentrations occur in fluids having intermediate enthalpy. Upon boiling, dissolved gases present in the liquid phase are strongly partitioned into the vapor phase and result in a rapid rise in fluid pH and supersaturation of calcium carbonate. As flashing progressively cools the fluid, however, the solubility of the carbonate minerals increases and, hence, the level of first flashing corresponds to the point of minimum carbonate solubility for the production fluids (Fig. 1).

Arnorsson (1989) also notes that, because of the much larger cross sectional area available for fluid flow in the reservoir (in the form of fracture permeability) as compared with the well bore cross-section, production conditions that favor first-boiling in the reservoir are much less likely to result in obstruction of flow by carbonate deposition. An attempt to model obstruction of rock permeability under such conditions was undertaken by Johnson (1989) who concluded that the rate of production decline would be a function of the degree of flashing, the fracture aspect ratio, and the proximity of the flash zone to the wellbore.

Field experience, reported by Armannsson (1989), Benoit (1989), Reed (1989), and Vaca et al. (1989), generally confirm Arnorsson's (1989) results. Reed (1989) reports on experience at Dixie Valley, Nevada, where a comparison of theoretical and measured values of calcium ion concentrations were used to detect carbonate deposition and to determine the approximate deposition rate in individual wells. A companion study by Benoit (1989) calculated the approximate mass of calcite deposited in the casing of production wells using caliper logs and found good agreement with the deposition rates calculated by Reed (1989). Benoit's (1989) results also showed a close correspondence between the level of first flashing in a well and the location of the heaviest carbonate depositions. A slightly different approach was taken at the Krafla field by Armannsson (1989) who used a comparison of calcium concentrations in downhole samples with those in production fluids to identify calcite depositing wells. This study also reported that, on occasion, the level of calcite deposition in a wellbore could be influenced by imperfections or discontinuities in the casing and that the maximum deposition did not always

correspond to the level of first flashing in the well.

Carbonate deposition has also been encountered in the high enthalpy geothermal fields at Cerro Prieto, Mexico (Mercado et al., 1989) and at the Miravalles field in Costa Rica (Vaca et al., 1989). In both of these fields, carbonate deposition appeared to be closely correlated with the depth of steam formation in each well. Although the rates of deposition of carbonate from these wells could be highly variable, depending on the fluid composition, some fluids contained sufficient calcium to completely obstruct well flow in a matter of a few weeks (Vaca et al., 1989).

Calcium carbonate scale in intermediate and low enthalpy geothermal systems has been reported by Lindal and Kristmannsdottir (1989) and by Vuataz et al.(1989). The former author reports on modelling results for fluid chemistry at the Kizildere power station in Turkey that shows calcite supersaturation if the water is allowed to boil and degas. They suggest that cooling the geothermal fluid from 147°C to 40°C in a heat exchanger, while still under pressure, will prevent supersaturation of calcite. A similar approach was taken by Vuataz et al. (1989) in dealing with calcite saturated waters in the sandstone aquifer at Melleray, France where a combination of sulfide and carbonate scale was responsible for deterioration of reinjection well permeability. Kristmannsdottir (1989) also notes that carbonate scale has been encountered in low temperature systems in Iceland when fluids are allowed to degas and, on occasion, when fluids from different temperature, or higher salinity, aquifers are allowed to mix.

Several different methods have been applied to control the formation of carbonate scale from geothermal fluids. Prevention of scale deposition in low enthalpy systems is typically controlled by limiting the extent of degassing and resultant pH changes that bring about supersaturation of carbonate minerals (Kristmannsdottir, 1989; Vuataz et al., 1989). In high enthalpy systems where boiling cannot reasonably be avoided, direct removal of scale formed in the flash zone by reaming the wells was found to be effective if scale deposition had not plugged the production aquifers or the slotted liner portion of the well (Benoit, 1989; Hurtado et al., 1989; Lindal, 1989; Thorhallsson, 1988; Vaca et al., 1989). The most significant recent improvement to this method reported by participants was the development of a rotating head that allowed an operator to ream a well during steam production; this protocol reduced the time required for completion of a well clean-out from a few weeks to a few days. Several investigators also reported that it was possible to reduce the frequency of reaming operations by increasing the diameter of the production liner in the well and by varying the depth the flash zone through the control of wellhead pressure (Benoit, 1989; Hurtado et al., 1989; Vaca et al., 1989). Finally, as noted above, Arnorsson (1989) suggested that allowing the flash zone to migrate out into the reservoir, where the fluid flow cross sectional area was much higher than that in the wellbore, could enable a well to produce for much longer periods. Hurtado (1988) noted, however, that if the flash zone became fixed at the point of fluid entry into the well, then obstruction of fluid flow could still occur quite rapidly, and, under these conditions, recovery of production could only be accomplished using the much more expensive method of acid treatment.

Chemical inhibition of carbonate scale deposition has been applied in several different geothermal environments (Lesmo and Sommaruga, 1989; Parlaktuna and Okandan, 1989; Pieri et al., 1989). Parlaktuna and Okandan (1989) performed laboratory investigations of synthetic organic polymers and phosphonate inhibitors and found that carbonate deposition could be reduced, but not eliminated, by proper addition of an inhibitor. They also found that excessive inhibitor addition above optimum concentrations could lead to the deposition of pseudo scale composed of calcium combined with the inhibitor anion (Fig. 2). Field tests of phosphonate inhibitor injection performed by Pieri et al. (1989) showed that calcite deposition could be controlled by the addition of inhibitor concentrations ranging from 10 ppm to 200 ppm in the brine phase. The higher addition rates were believed to be required by the higher dissolved solids concentrations in some wells; however, this investigation also reported that inhibitor-induced corrosion of the downhole injection system could cause the loss of the injection tubing. This problem was alleviated by the use of a composite injection system consisting of a plastic injection tube jacketed with Incoloy 825.

SILICA SCALE

Silica deposition has been encountered in virtually all high enthalpy, liquid- dominated, geothermal fields. Investigators from Mexico (Hurtado et al., 1989; Mercado et al., 1989), Iceland (Kristmannsdottir, 1989; Lindal, 1989), Turkey (Lindal and Kristmannsdottir, 1989), Greece (Hibara et al., 1989; Karabelas et al., 1989; and Koutinas, 1989), and Japan (Itoi et al., 1989) report the occurrence of silica deposition in geothermal facilities.

A review of silica chemistry (Chan, 1989) indicates that the mechanism of deposition is neither simple nor well understood. Unlike calcite, which appears to precipitate soon after it reaches supersaturation, silica deposition is kinetically controlled and can be delayed by minutes to hours after its saturation limit has been exceeded (Chan, 1989; Hurtado et al., 1989). According to Chan (1989), more recent research results suggest that surface charge effects control particle nucleation during the early stages of silica polymerization but surface rearrangement reactions control continued particle growth as silica precipitation proceeds. Factors affecting surface charge of the silica polymer in solution, and therefore its precipitation rate, include pH, trace metal concentrations, and the ionic strength of the fluid. A detailed study of the interaction of silica with dissolved salts, by Yokoyama et al. (1989), found that aluminium had a strong influence on polymerization rates and could either retard deposition (at lower pH) or accelerate deposition (at higher pH); they attribute these effects to the influence that the adsorbed aluminium ion has on the surface charge of the suspended silica polymer in solution. The reported presence of high concentrations of other transition metals in silica deposited at many other geothermal facilities (Gallup, 1989; Hurtado, 1989; Karabelas, 1989; Kristmannsdottir, 1989; Lindal, 1989; Lindal and Kristmannsdottir, 1989) suggests that silica deposition may be sensitive to a variety of other transition metals as well. Because silica precipitation from geothermal fluids can occur over periods of minutes or hours after supersaturation occurs, silica scale has been found throughout the fluid handling equipment of several geothermal facilities: Mercado et al. (1989) and Hurtado et al. (1989) report that silica scale deposits in production wells and surface brine piping at the Cerro Prieto field. Hibara et al. (1989) and Karabelas et al. (1989) have noted substantial rates of silica deposition in the surface piping at the Milos field and Itoi et al. (1989) describe the loss of injection capacity of geothermal wastewater reinjection wells due to silica deposition downhole. Other investigators also have reported the formation of silica scale deposits in steam handling and turbine inlet systems (Koutinas, 1989). In spite of earlier suggestions that some volatile form of silica might be present in the steam phase, the detection of moderate to high levels of chloride ion in the steam-line condensate drains indicates that this phenomena is the result of brine aerosol carry-over and evaporation at the turbine inlet nozzles (Cohen, 1988).

Siliceous scale is typically inert to most chemicals and, once deposited, is very resistant to mechanical removal. Hence, most treatment methods focus on prevention of silica deposition or on controlling the morphology of the silica deposited. Efforts to prevent deposition of scale on surface equipment have included restricting steam separation to temperatures at which silica supersaturation is minimized (Hibara et al., 1989; Hurtado et al., 1989; Karabelas et al., 1989) and acidification of the brine phase to inhibit silica deposition (Gallup, 1989; Gudmundsson, 1989; Gudmundsson and Einarsson, 1989; Lindal, 1989). Other workers have dealt with silica by accelerating its deposition rate to reduce silicic acid concentrations to near saturation and thus prevent further deposition downstream. This approach has been used at Cerro Prieto where flashed brine was allowed to age and was then treated with lime and organic flocculating agents; after a period of settling in a clarifier, the brine was then suitable for reinjection into the reservoir formation. Similar silica recovery studies were performed at the Svartsengi geothermal plant where it was found that the temperature and length of time allowed for aging the fluids prior to addition of caustic had a substantial effect on particle sizes and surface areas of the material recovered (Thordarsson and Tomasson, 1989). The latter characteristics are important both for their control of the rate of settling of the silica from the brine and also for their impact on the value of the silica as a marketable

byproduct. This study indicated that surface areas in excess of 200m^2 per gram could be achieved under appropriate treatment conditions.

A somewhat different approach to silica removal was reported by Gudmundsson and Einarsson (1989), who have conducted experiments on silica polymerization and scale control using electric and magnetic fields. Their results suggest that passage of silica supersaturated brine through a zone of crossed magnetic and electrical fields could substantially increase the rate of silica polymerization and subsequent settling. It is postulated that the electrical and magnetic fields can disrupt the electrical double layer surrounding the silica polymers and thereby reduce the strong surface charge effects responsible for the slow rate of silica polymerization.

Removal of silica scale deposited from steam-phase aerosol has been attempted with some success. It was reported that periodic injection of deaerated water upstream of the turbine inlet nozzles was able to remove scale from the nozzles and the turbine blades (Koutinas, 1989). This technique also has been successfully used in Hawaii at the HGP-A generator facility; however, some hazards inherent to the technique include thermal shock to the turbine, rotor vibration, and turbine blade erosion (Koutinas, 1989).

METAL SULFIDE AND OXIDE SCALE

Mixed metal sulfide and oxide scale deposition has been reported to occur in virtually every type of geothermal system including those having low, intermediate, and high enthalpy. Criaud and Fouillac (1989) note that low enthalpy fluids containing high concentrations of dissolved solids can cause severe corrosion of mild steel production casings. The iron liberated by corrosion reacts rapidly with sulfide-rich geothermal fluids and can produce higher deposition rates of metal sulfide scale than is typically found in higher temperature environments. Ungemach and Roque (1988), and Honegger et al. (1989), provide a detailed account of such corrosion damage in the utilization of low to intermediate temperature fluids for heating applications in the Dogger Aquifer in the Paris basin. They find that corrosion of mild steel production casing results in deposition of large quantities of iron sulfide scale in the production and injection wells. The iron phases identified include mackinawite, pyrite, pyrrhotite, and lesser amounts of other iron and calcium carbonate species. Although the mechanism of corrosion attack is not unequivocally identified, possible candidate processes that are consistent with the data presented include: bacterial attack (as indicated by high concentrations of sulfur mediated flora (Honegger et al., 1989); chemical attack by H_2S, or CO_2; or galvanic attack (Ungemach and Roque, 1988).

In high enthalpy systems, metal sulfides and oxides are frequently deposited directly from the geothermal fluids upon a change of phase or pH. Lindal and Kristmannsdottir (1989) report mixed metal deposits consisting of iron and copper sulfides, zinc oxide, and silica downstream of the pressure reduction nozzles of the Reykjanes geothermal plant in Iceland. Kristmannsdottir (1989) also notes the presence of high rates of deposition of metal sulfide and oxide scale at several Krafla wells. In the latter field, the deposition occurred both in the surface facilities and downhole in some of the production wells. Other high enthalpy fields in which metal sulfide/oxide scale deposition was reported include: Milos, where high rates of mixed metal sulfide/oxide/silica scale deposits occurred in the surface equipment (Hibara et al., 1989; Karabelas et al., 1989; and Koutinas, 1989); Cerro Prieto, where metal silicates formed predominantly downhole in the flash zone (Mercado et al., 1989); and at the Salton Sea field where iron silicate formations were found in the surface equipment (Gallup, 1989).

The rate of metal sulfide/oxide deposition in most of the high enthalpy systems is controlled by the degree of pH change accompanying the fluid flashing process and by the (usually low) concentration of metal ions (Andritsos and Karabelas, 1989; Karabelas et al., 1989). The latter factor usually limits the rate of deposition of metal sulfides in high temperature systems but, under some conditions such as the extremely high salinities at the Salton Sea field or when large quantities of acid magmatic gases are injected into the reservoir fluids (as has occurred at Krafla), metal ion concentrations can be quite high, resulting in rapid rates of scaling. Although iron release due to casing corrosion was not indicated to be as great a problem in high enthalpy fields as was reported for the low enthalpy

systems, Pye et al. (1989), and Truesdell et al. (1989), reported on excessive corrosion rates that occur in extremely high salinity brines and in fields where acid gases are produced, respectively. The latter authors suggest that dry steam production from a chloride-rich brine can lead to the evolution of gaseous hydrochloric acid which will attack well casings or surface equipment wherever it comes into contact with condensed steam. This mechanism is suggested to account for the extreme rates of metal sulfide/oxide deposition that have been observed in some of the Krafla, Larderello, and Geysers steam wells.

Several authors reported on possible treatment methods for dealing with mixed metal sulfide/oxide deposition. In low enthalpy systems, attempts made to inject fatty amine corrosion inhibitors and alkaline polyacrylate crystal growth inhibitors (dispersants) to protect the production casing and to prevent formation of metal sulfides were met with mixed success (Honegger et al., 1989; Ungemach and Roque, 1988). Although other treatment chemicals are being explored and tested, a further alternative suggested was to install a fiberglass liner in conventionally completed wells and to purge the annulus between the casings with corrosion-inhibited water (Ungemach and Roque, 1988). Treatment of metal silicate scale deposition from high enthalpy fluids included the addition of acid (Gallup, 1989) and increasing the pressure of separation of steam from the brine phase (Koutinas, 1989). In a study of methods to alleviate casing corrosion in the high enthalpy system at Salton Sea, Pye et al. (1989) found that the only material that was sufficiently resistant to those geothermal brines was Beta-C titanium; all other alloys were either subject to general corrosion or to extreme rates of pitting. Corrosion resulting from the presence of hydrochloric acid in the steam phase was not directly treatable for prevention of mass loss or deposition of metal sulfide/oxide scale. It was noted, however, that replenishment of reservoir liquid reserves might help alleviate the generation of acid from a hypersaline boiling zone in the reservoir.

SCALE FORMATION ON HEAT EXCHANGERS

Several investigators reported on field and theoretical studies of scale deposition on heat exchanger surfaces. Gunnlaugsson and Einarsson (1989), and Kristmannsdottir et al. (1989), discuss the deposition of magnesium silicate minerals that occurs when mixtures of cold fresh groundwater and geothermal water are used as secondary fluids for use in domestic heating. Their investigation showed that mixing of geothermal fluids with deaerated magnesium rich groundwaters produced a smectite-like mineral formation on heat exchanger surfaces. By limiting the degree of deaeration and adding a small amount of geothermal steam (containing hydrogen sulfide), they found that they could successfully limit the formation of the silicate scale. In a separate study, Hernandez-Galan and Plauchu-L. (1989), investigated the rates of scale deposition associated with heat extraction from waste geothermal brines at the Los Azufres geothermal field. Their results showed that the rate and physical characteristics of the scale changed along the fluid flow path although data was not available on the chemical composition of the mineral phases deposited. Their results also indicated that the fluid compositions available at Los Azufres would allow the successful operation of a properly designed shell and tube heat exchanger for periods of up to 2000 hours before scale removal would be required.

The results of mathematical models of scale formation and deposition under a variety of conditions were presented by Yung et al. (1989) who described the results of laboratory and computer studies of the interactions among the forces acting on scale nuclei in a flowing fluid. The more important factors controlling particle deposition or reintrainment were: the respective surface charges of the entrained particle and solid substrate; the fluid viscosity; and turbulence at the fluid/substrate interface. One goal of the computer model currently under development is the calculation, for a known fluid composition, of the fluid velocities required in a heat exchanger to minimize deposition of a known solid phase.

A somewhat different approach to the same problem was presented by Fryer (1989) who showed that it was possible to calculate an optimum residence time for a scale-producing fluid in a heat exchanger. This type of modelling was

shown to be of particular value when dealing with the formation of scale minerals (such as silica) that deposit through a two-stage process: direct deposition from solution and particle nucleation followed by migration from the bulk solution to the solid substrate (Fig. 3). It was shown that, with the aid of available models of mineral solubility and nucleation rates, fluid residence times could be calculated that would minimize scale deposition in a heat exchanger.

REINJECTION STUDIES

Other modelling efforts presented at the workshop included investigations of solid deposition from fluids that were to be injected into geothermal reservoirs. Crecraft and Koenig (1989) presented the results of chemical modelling that was performed for the sequence of phenomena undergone by injectate as it encountered the changing thermal and chemical conditions during its (re-) entry into the reservoir (Fig. 4). In their model, they consider injection of power plant condensate and treated municipal wastewater into the geothermal reservoir at The Geysers geothermal field. Their analysis showed that if only the relative solubilities of the various mineral phases present, were considered, there could be a net increase in the reservoir permeability due to dissolution of quartz from the reservoir rock. They also point out, however, that limitations imposed by the mass of available quartz in the reservoir and the relative kinetics of deposition and dissolution of the different mineral species could prove to be controlling considerations in whether a given fluid could successfully be injected into a geothermal reservoir on a long-term basis.

Milodowski et al. (1989) performed a laboratory investigation of the chemical consequences of injecting surface groundwaters and seawater into a granitic hot dry rock system in the United Kingdom. The results of their work indicated that groundwater reacting with granites would produce relatively minor amounts of secondary clay formation and that the resulting fluid would be somewhat alkaline. Reactions with seawater at similar temperatures produced substantial amounts of secondary mineralization and a much more aggressive fluid phase having a pH of approximately 3.5. In a companion study, conducted at Miravalles geothermal system, Rochelle et al. (1989) showed that a combined analysis of the secondary mineralogy, the fluid chemistry, and the reservoir temperature could be used to determine both present and past equilibrium conditions occurring in the reservoir fluid/rock system.

SUMMARY AND CONCLUSIONS

The papers presented at the International Workshop on Deposition of Solids in Geothermal Systems have demonstrated that precipitation of dissolved solids from geothermal fluids is a virtually ubiquitous phenomenon which occurs in geothermal fluids having a wide range of chemistries and at temperatures ranging from less than 100°C to more than 350°C. The reports presented also indicate that the precipitation of solids from natural fluids is a highly complex physical and chemical process that is still poorly understood and over which we have only limited control. Before we can hope to gain better control over the scale deposition process, further research will be required into the physical chemistry of (carbonate and metal sulfide) crystal nucleation and growth, (silica) colloid nucleation and polymerization, the physical and chemical processes occurring in the bulk fluid and at heat exchanger surfaces, and the chemistry of water/dissolved ion/rock interactions. Through knowledge gained from these studies we will be able to develop new and better equipment and process designs that will allow us to make the most cost-effective use of the heat present in geothermal fluids.

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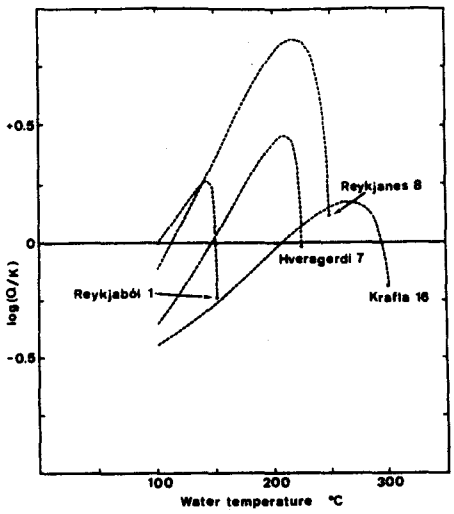

Fig. 1. Curves demonstrate the sequence of change in the state of calcite saturation as a carbonate-rich geothermal fluids begin to boil and degas. As boiling is initiated the majority of the dissolved gases are almost immediately lost, driving the pH upward and decreasing the solubility of calcite. As more steam forms, the fluid temperature falls and the solubility of calcite increases. (From Arnorsson (1989), Figure 7, this volume).

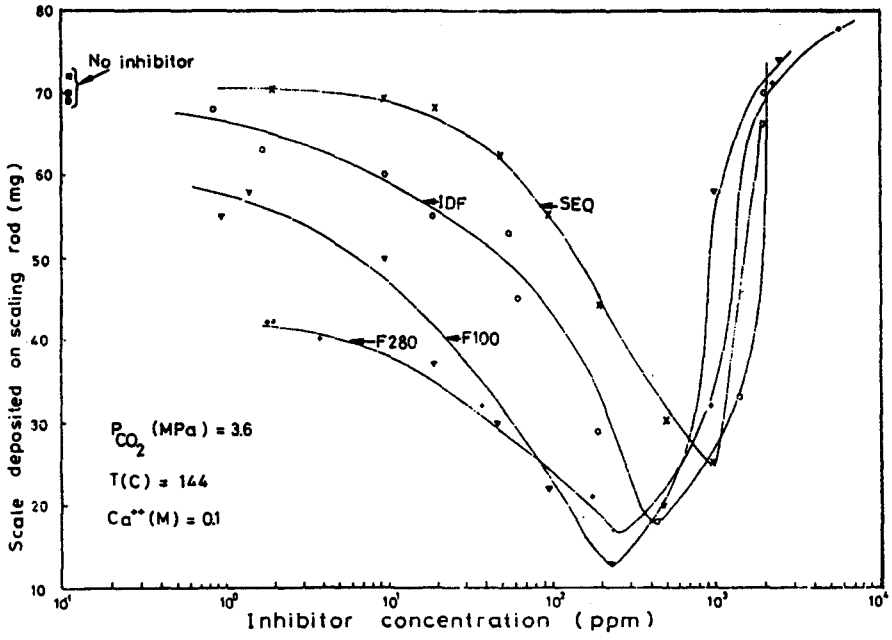

Fig. 2. Curves show the variation in deposition rate of carbonate scale as a function of inhibitor added. At progressively increasing dosages of inhibitor the mass of scale deposited decreases to a minimum value; above this optimum dosage rate, the mass of scale increases rapidly due to the formation of psuedo scale formed from the scale cation (Ca) and the inhibitor anion. (From Parlaktuna and Okandan (1989), Figure 3, this volume).

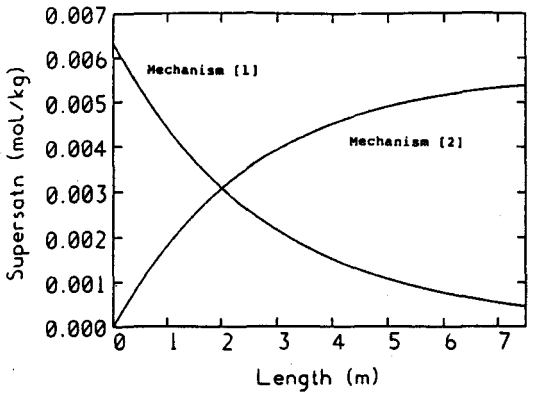

Fig. 3. Hypothetical curves showing the variations in supersaturation (or deposition rate) of a scale mineral that can form through two different mechanisms along a heat exchanger. An example of this type of scale deposition might be silica deposition: Mechanism (1) would correspond to direct deposition of silicic acid monomer onto a solid substrate, whereas Mechanism (2) would correspond to deposition of silica polymers that had first formed in the bulk solution and only later attached to the substrate. (From Fryer (1989), Figure 3, this volume).

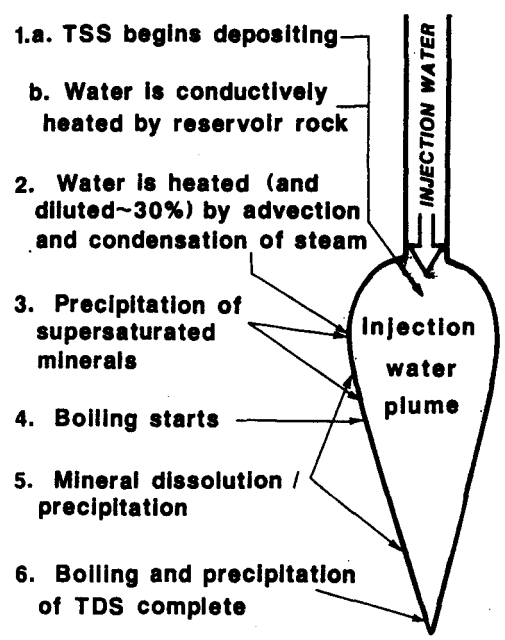

Fig. 4. Conceptual diagram of the sequence of physical and chemical changes undergone by reinjected wastewater as it is returned to a steam dominated geothermal reservoir. The locations of the various reactions would be expected to change with time as conductive heating of the water cools the rock immediately around the injection point and as the zone of condensation and dilution moves outward and downward from the reinjection zone. (From Crecraft and Koenig (1989), Figure 4, this volume).